LASER ATMOSPHERIC INSTRUMENTATION AND MEASUREMENT

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INTRODUCTION

The development of the high intensity giant pulse laser has placed new emphasis on methods of remotely sensing the properties of the atmosphere. The characteristics of the laser coupled with developments in computer and photodetector technology enable the investigator to significantly extend light scattering methods of observing the atmosphere and perhaps for the first time place such measurements on firm theoretical basis. In this paper two NASA laser radar research programs currently in progress will be described, and a number of potential applications of laser radar to problems in meteorology and atmospheric research will be discussed. In addition, the instrumentation developed to probe the atmosphere with lasers will be described as well as our plans for future research.

I. SCATTERING OF LASER RADIATION IN THE ATMOSPHERE

In order to establish a basis for the interpretation of laser returns from the atmosphere, we shall briefly present in this section a summary of Mie calculations at laser wavelengths for scattering by a clear atmosphere.

The radiation backscattered by a volume element of the atmosphere located a distance S from laser, expressed as the power incident on a coaxial receiver, is given by

$$P(S) = \frac{cEA_R q^2(S)\ \sigma(S)}{2S^2} \tag{1}$$

where E is the transmitted energy, A_R is the area of the receiver, $q(S)$ is the transmissivity of the atmosphere $\sigma(S)$ is the backscattering volume cross section of a volume element located at S, and c is the velocity of light. In equation (1) the scattering volume is assumed to be a point source which requires the beam divergence and pulse width of the laser to be small.

The volume cross section and transmissivity will be interpreted according to a scattering model which assumes the atmosphere to be a mixture of molecules, described by Rayleight theory, and aerosols, described by rigorous Mie theory.

If the atmospheric absorption is neglected the transmissivity is given by

$$q(S) = \exp\ - \int_0^{S'} \beta(S)\ dS \tag{2}$$

where $\beta(S)$ is the sum of the molecular and aerosol scattering coefficients.

Rayleigh Scattering

The absolute Rayleigh volume cross section for backscatter from the molecular component is

$$\sigma_M = k^4 \bar{\alpha}^2 N(z)\ f \tag{3}$$

where

k = wave number of incident radiation, $2\pi/\lambda$

$\bar{\alpha}$ = polarizability

$N(z)$ = number density

and

$$f = \frac{3(2 + \Delta)}{6 - 7\,\Delta}$$

where Δ is the depolarization factor. For atmospheric air, G. de Vaucouleurs (1951) has measured $\Delta = 0.031$, and therefore $f = 1.054$.

The scattering coefficient for the molecular component is

$$\beta_M(z) = \int_0^{2\pi} \int_0^{\pi} \tfrac{1}{2}(1 + \cos^2\theta)\ \sigma_M(z)\ \sin\theta\ d\theta\ d\varphi \tag{4}$$

Large Particle Scattering

Assuming that the particulate matter present in the atmosphere may be considered a polydisperse collection of homogeneous spheres of average index η, the volume cross section is given by

$$\sigma_A(z) = \int_{r_1}^{r_2} \frac{i\ (\alpha,\eta,\theta) + i\ (\alpha,\eta,\theta)}{2k^2}\ dn(r,z) \tag{5}$$

where $i_{1,2}(\alpha,\eta,\theta)$ are the Mie intensity functions for light with electric vector perpendicular and parallel, respectively, to the plane through the direction of propagation of the incident and scattered radiation, r is the radius of the scatterer, $\alpha = 2\pi/\lambda$ is the particle size parameter, $dn(r,z)$ is the number density of particles with radius between r and $r + dr$ at altitude z, and θ is the scattering angle measured between the direction of the incident and scattered radiation.

Similarly, the scattering coefficient for such a collection is given by

$$\beta_A = \int_{r_1}^{r_2}\int_0^{\pi} \frac{\pi\ i_1(\alpha,\eta,\theta) + i_2(\alpha,\eta,\theta)}{k^2} \sin\theta\ d\theta\ dn(r,z) \tag{6}$$

A computer program has been written to evaluate the integral expressions in equations (5) and (6) for an arbitrary choice of aerosol parameters, and we shall compare the results of an atmospheric scattering model calculation with experimental measurements in a section to follow.

Instrumentation

Three laser radar systems have been constructed to date and have been used to probe the atmosphere.

An airborne system, installed in a T-33 type jet aircraft, consists of a ruby laser transmitter and a refracting telescope receiver whose axes are alined parallel. The laser produces pulses of approximately 0.1-joule energy and of 20-nsec duration with a beam divergence of 1 mrad. The backscattered laser energy is collected by a receiver which has a field of view of 3 mrad and an effective collecting aperture of 0.1 meter.

The optical bandwidth of the receiving system is determined by a temperature-controlled interference filter with a spectral bandwidth of 11.75 Å centered at 6943 Å. The photomultiplier detector used in this system has 16 amplifying stages and a photocathode with an S-20 spectral response. The laser output monitor is calibrated by comparison with a thermopile calorimeter and the spectral response of the receiver was determined using a standard lamp; in consequence, the airborne system can make absolute measurements of the backscattering cross section.

This laser radar system was constructed and flown to explore the feasibility of using laser radar as a clear air turbulence detection device. This system was not successful in detecting atmospheric turbulence; however, it has made excellent absolute measurements of the scattering properties of the atmosphere which will be described in a section to follow.

The first ground-based system designed consists of a ruby laser and a 60-inch parabolic search light mirror positioned in a steerable mount with their axes parallel. The laser produces a 1- to 2-joule pulse of 20-nsec duration at 6943 Å, and is temperature controlled to prevent detuning into an atmospheric absorption band. A 14-stage photomultiplier detector with S-20 response is positioned near the focal plane. The optical bandwidth of the system is limited to about 700 Å by the combination of a red filter and the S-20 photocathode response. The acceptance angle of the mirror is reduced to approximately 10 mrad by a stop at the focal plane. In view of the wide spectral bandwidth of this system, it can not of course be used to make measurements during the daylight hours. At night, however, the sky background radiance is down from its daylight value by approximately six orders of magnitude and its contribution to the system noise is negligible for altitudes below approximately 30 km. As an indication of the performance of the system during nighttime operation we have listed in table 1 values of the signal to noise ratio for several altitude regions.

TABLE 1.- SYSTEM DETECTION CAPABILITY

Altitude (km)	Signal to noise ratio
5	200
10	76
15	37
20	20
26	10

A schematic diagram of a second, more advanced, ground-based system which has been constructed to probe the upper atmosphere is given in figure 1. This system consists of a 31-inch Newtonian telescope receiver with a ruby laser transmitter. The acceptance angle of the receiver is 1 mrad and the optical bandwidth is limited to 20 Å by an interference filter.

Results

Observations of the Clear Atmosphere

Typical observations of the clear atmosphere are shown in figure 2. A composite profile extending to about 22 km has been constructed from three laser shots. The solid curve in the figure is the total return calculated for the U.S. Standard 1962 Atmosphere and an aerosol component based on Rosen's direct sampling measurements. A fast decrease in aerosol number density in the first 2 kilometers is evident; in this region the scattering is predominantly of aerosol origin. The scattering from about 2.5 to 12 kilometers appears to be predominantly of molecular origin; small increases in the absolute cross section, however, are noted throughout and indicate the presence of local concentrations of aerosols. A deviation from molecular scattering appears at about 12 kilometers and increases to about a factor of two at 19 kilometers.

Shown in figure 3 are the results of a series of simultaneous measurements of the backscattering volume cross section of a clear atmosphere by the airborne and ground systems. The profile measured with the ground-based system has been normalized to the airborne data at 7.2 km. As is evident in the figure the two sets of experimental data agree very well and in addition agree with the model calculation above 2.5 km. Below 2.5 km the measured profile deviates significantly from the calculated profile. This deviation is indicative of the aerosol concentration in the vicinity of a subsidence inversion which existed in the vicinity of 1.8 km.

Observation of Clouds

No systematic observations of cloud systems have been made nor has any attempt been made to fit polydisperse models to our measurements. The observations made to date, however, clearly demonstrate that laser radar constitutes an excellent method for observing cloud systems.

The structure evident in figure 4(a) is a high cirrus cloud extending from 9 to 12 km; also evident is an altostratus cloud at 5.85 km of thickness 300 m. The return in figure 4(b) shows a cirrus cloud system centered at approximately 11.85 km. Figure 4(c) shows another cirrus cloud which at the time of observation was stratified into three layers. The base of this system was 11.7 km, while the top was 13.35 km. Figure 4(d) is an example of the return from a dense cirrus cloud similar to that found in figure 4(a) extending from 8.7 km to 11.25 km. In addition, it should be noted that laser radar can detect clouds in their earliest stages of formation.

Observations of Turbulent Regions of the Atmosphere

In a series of experiments conducted over Williamsburg and Wallops Island, Virginia, a T-33 type jet aircraft instrumented with a recording accelerometer was directed into regions of the clear atmosphere where enhanced backscatter of ruby laser radiation was observed by an experimental ground-based pulsed ruby laser radar system. In 33 cases, established over 7 nights of observation, the aircraft encountered light turbulence (vertical acceleration generally in the range 0.10 to 0.25g) in clear air in regions of enhanced backscatter. In addition, the aircraft conducted a general search for turbulence to heights of 12 km above the field station and did not encounter turbulence in regions where no enhancement in backscattered signal was evident.

Figure 5 shows oscilloscope recordings of two such examples in which the aircraft encountered turbulence. A scattering enhancement is clearly evident in figure 5(a) from 3.3 to 4.05 km; the pilot reported light turbulence (0.1 to 0.2g) in clear air from 3.7 to 4.05 km. In figure 5(b), an enhancement extending from 2.4 to 3.1 km is evident; the pilot reported light turbulence (0.1 to 0.2g) in clear air in three layered regions extending from 2.5 to 2.8 km. Radiosonde measurements made at Wallops Island, Virginia, (75 miles northeast of Williamsburg) on this evening indicated that a subsidence inversion existed at an altitude of 3.1 km; light turbulence was presented beneath this inversion.

Atmospheric Wind Velocity Program

The program which has just been described seeks to explore only one aspect of the laser radar technique. In a second program, which is being conducted at the Marshall Space Flight Center, applications of the CO_2 laser doppler technique to atmospheric measurements are being investigated.

Since the CO_2 laser doppler technique has been successful in making wind tunnel velocity measurements, consideration is being given to extending the development of this type of instrumentation to measurements of atmospheric wind velocity and turbulence. For this type of instrumentation, the S/N power at the output of the receiver for a monochromatic source is

$$S/N = \frac{Q\, P_r\, P_{lo}}{Bhf\ (P_{lo} + P_n + P_{amp})}$$

where Q = detector quantum efficiency

P_r = received signal power

P_{lo} = local oscillator signal power

P_n = equivalent optical noise power

P_{amp} = equivalent noise figure power of post detection amplifier

B = electronic bandwidth

h = Planck's constant

f = transmission frequency

In a coherent detection process, one may increase the local oscillator power to outweigh the effects of the additional noise contributing terms. As a result the S/N equation becomes equal to the product of the detector quantum efficiency and the received signal power and inversely related to the electronic bandwidth, transmission frequency and Planck's constant. The advantages of using a CO_2 laser system for atmospheric studies of this type are:

1. Since the coherent scattering volume increases as the square of the wavelength, the S/N increases as the cube of the wavelength of the incident radiation. The CO_2 laser takes maximum advantage of λ^3 dependence of the signal to noise ratio.

2. The laser is efficient in the use of prime power ($\approx$10%)

3. Alinement is not critical because of long wavelength

4. The CO_2 laser has the highest CW output power available and substantial power increases are predicted in the near future.

Given in figure 6 is a schematic diagram of a preliminary experiment performed in the atmosphere with a 10 watt single frequency CO_2 laser.

Measurements were made of the doppler return for various types of weather conditions ranging from very clear to rainy, and a general correlation has been obtained with the approximate wind velocity prevalent at that time of day. Recently a 25-watt stable single frequency CO_2 laser has been developed to improve these measurements.

Future Research Program

Our plans for future work at the Langley Research Center may be divided into three areas:

A. Extension of the laser radar technique to include multiple wavelength measurements and Raman scattering

B. Development of instrumentation

C. Investigations of the potential application of laser radar to fundamental problems in upper atmospheric research, meteorology, oceanography, and air pollution

A. Extension of the Laser Radar Measurement Technique

1. Multiple laser wavelength measurements:

The equations developed in section 2 for the molecular and aerosol scattering components suggest a natural extension of the measurement technique to multiple laser wavelengths. Given in figure 7 are scattering profiles for three laser wavelengths computed for an aerosol component based on direct sampling measurements and a molecular component based on the U.S. Standard Atmosphere 1962. The curves given in figure 7 indicate the relative contribution of the aerosol and molecular scattering components at the laser wavelengths 1.06μ, 0.6943μ, and 0.3472μ, and it can be shown that measurements at these wavelengths will completely characterize the atmospheric aerosol.

2. Raman scattering:

If the spectrum of laser radiation scattered by the atmosphere is examined, it will consist of an intense line characterized by the frequency of the incident radiation, and in addition a series of very weak lines produced by inelastic scattering by the various molecular species present in the atmosphere. When an incident photon is inelastically scattered by a molecule, it either gives up energy to the scattering molecule or it takes energy from it. Since the molecule can only give up or absorb energy between stationary states, the inelastically scattered or Raman scattered radiation is characteristic of the scattering molecule. Measurement of the Raman lines associated with laser scattering appears to be a very promising technique for studying the atmosphere. It may be possible to use this technique to measure the transmissivity of the atmosphere, the vertical profile of the constituents of the atmosphere and possibly the temperature profile. It should be noted, however, that the Raman scattered radiation represents a very small fraction of the total scattering and, in consequence, it will be a very difficult measurement to make.

B. Instrumentation

Given in figure 8 is a schematic diagram of an improved optical radar system which is currently in the design phase. It is anticipated that construction of this system will be completed by the middle of 1969.

The system consists of a steerable 48-inch f/2 Cassegrain telescope receiver which will be trailer mounted. Two laser systems, ruby and neodymium, will be mounted on the receiver with 10:1 collimators. It is anticipated that both of these laser systems will have a pulse repetition rate of approximately 10-15 pulses per minute with a transmitted energy in the range 3-5 joules. In addition a relatively advanced data acquisition system will be incorporated in the optical radar as shown in figure 8.

C. Planned Investigations of Potential Applications of Laser Radar

1. Meteorology

Laser radar is in many ways similar to conventional weather radar with the added attraction that it is many orders of magnitude more sensitive. It is, in consequence, a very useful tool for meteorological investigations. One important potential application is in the area of weather modification. An important requirement in cloud seeding experiments is a method for determining the possible rain content of a cloud system prior to seeding. It is likely that laser radar can provide an economical and accurate method of determining the cloud systems that can be profitably seeded. A second area in which laser radar may have an important potential application is in the study of turbulence. Preliminary results obtained which were briefly described in a previous section indicate that it may be a promising technique for the study and detection of atmospheric turbulence.

2. Upper atmosphere measurements:

Direct measurements of the atmosphere can be made to altitudes of approximately 30 km by balloon-borne instruments, and above 150 km satellite experiments provide useful data. The region 30-150 km, however, remains accessible only to rocket probes. In view of the fact that it is both difficult and expensive to make systematic measurements with rocket probes, little is known of the latitudinal, seasonal, and diurnal variations in density of the altitude region 30-150 km. Laser radar is a very promising and inexpensive technique for providing systematic measurements of the molecular and particle density of this altitude region.

Air Pollution

Laser radar provides an accurate and convenient method for monitoring pollutants introduced into the atmosphere in industrial areas. An important aspect of the laser radar method of monitoring pollutants is that it provides a remote measurement.

Oceanography

The National Academy of Science has recognized the air-sea interaction as a research area of fundamental importance and has recommended that it be subjected to extensive study. At least, in principle, laser radar can determine the coefficient of eddy transfer in the lower atmosphere by measuring the vertical distribution of salt particles and other aerosols over the ocean. In addition, it can materially aid convective studies over the ocean by providing accurate measurements of the distribution and transmissivity of cloud systems.

At Marshall Space Flight Center further development of the CO_2 laser doppler technique is being considered in the following areas:

1. Perform precise triangulation doppler measurements to compare with anemometer data

2. Develop a three-dimensional ground wind measuring instrument capable of one meter resolution at 500 meters altitude

3. Determine the feasibility of detecting trailing vortices behind aircraft landing or taking off at airports

4. Since the laser doppler technique provides a direct measurement of turbulence, consideration is being given to the possible development of a CO_2 doppler radar as a clear air turbulence detection system.

Future Developments Required

Laser radar systems have excellent potential for a number of important applications with the present state of technology; however, with additional research and development its capabilities can be increased markedly. Fruitful areas for research and development are:

1. Improvement in laser power with increased pulse repetition rate

2. Improved reliability of high-power laser systems

3. Improvement in the efficiency of harmonic generation materials

4. Development to increase quantum efficiency of detectors in visible and infrared

5. Development of interference filters for receiver with small spectral bandwidth and high transmission

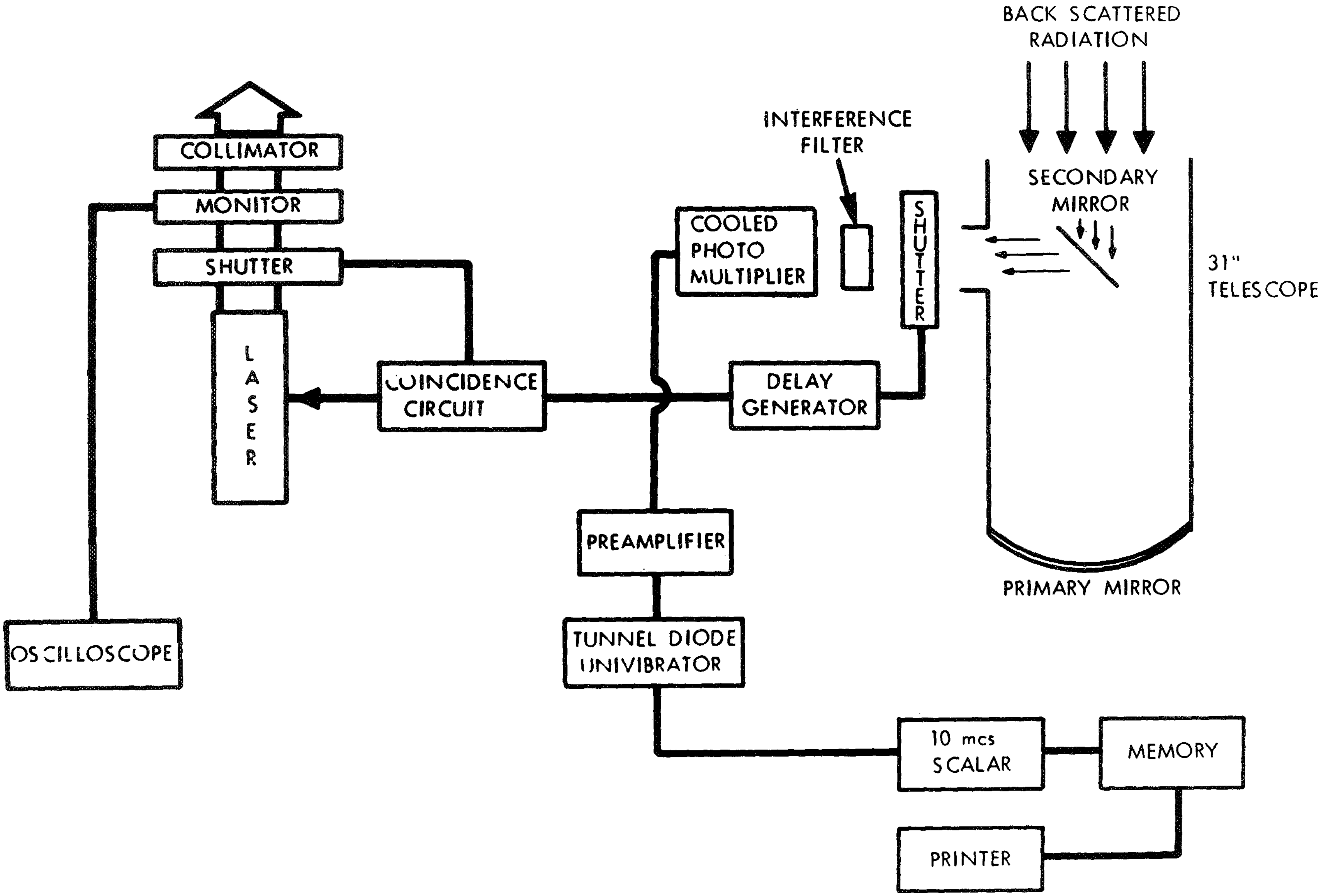

Figure 1.- Schmatic diagram of laser radar system for upper atmosphere measurements.

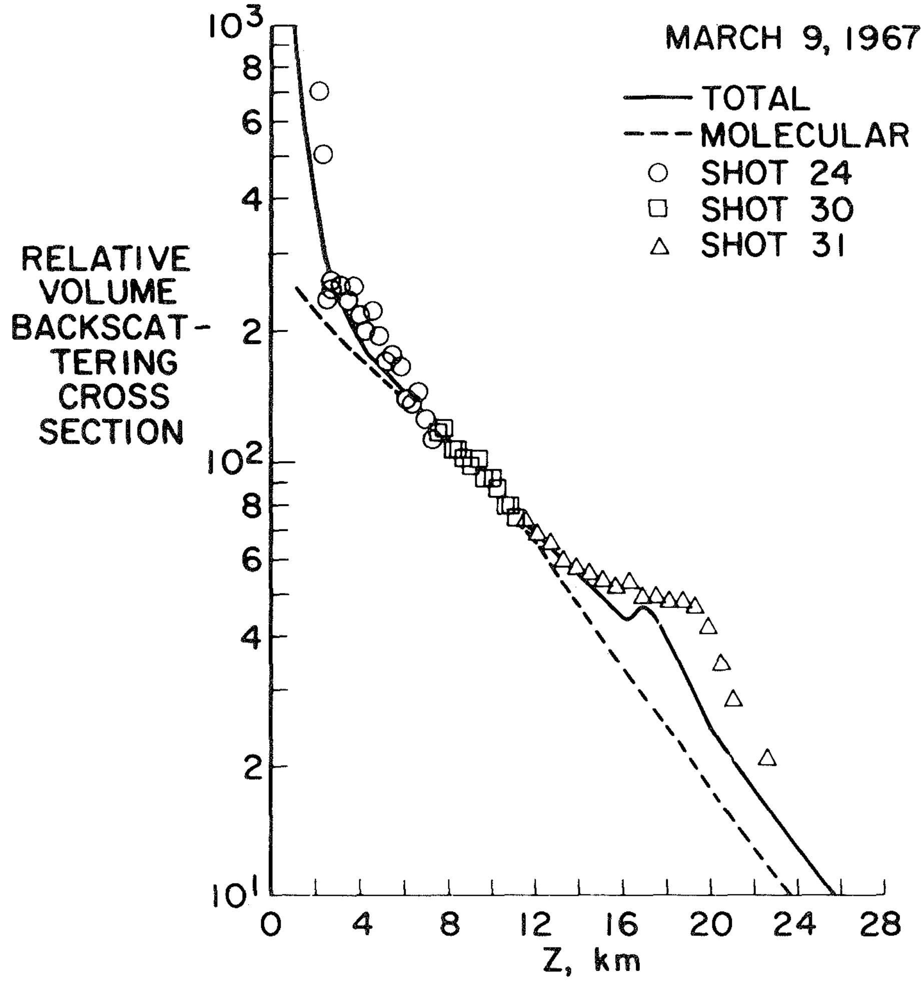

Figure 2.- Laser radar return from the clear atmosphere.

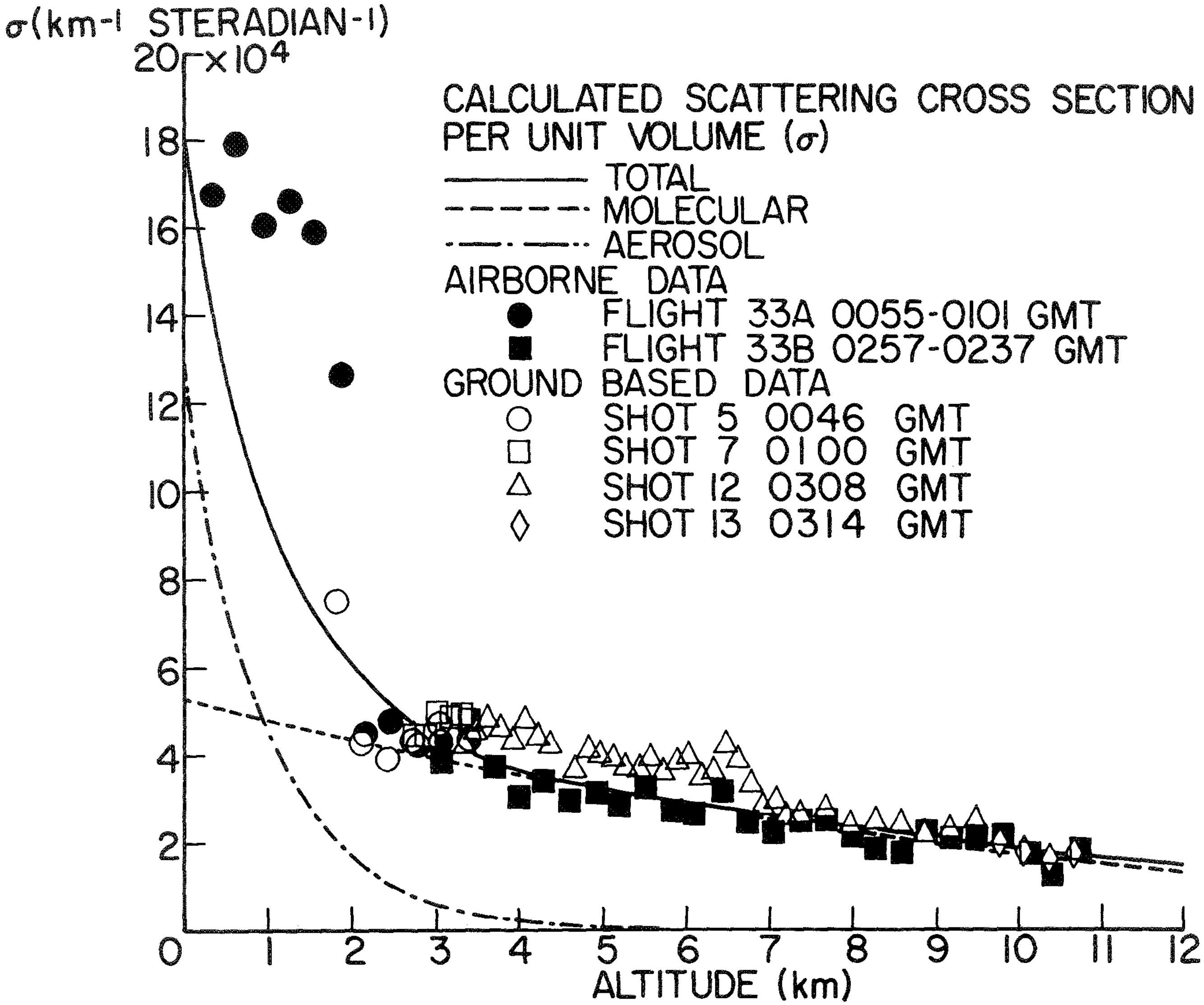

Figure 3.- Simultaneous ground-based and airborne laser radar measurements.

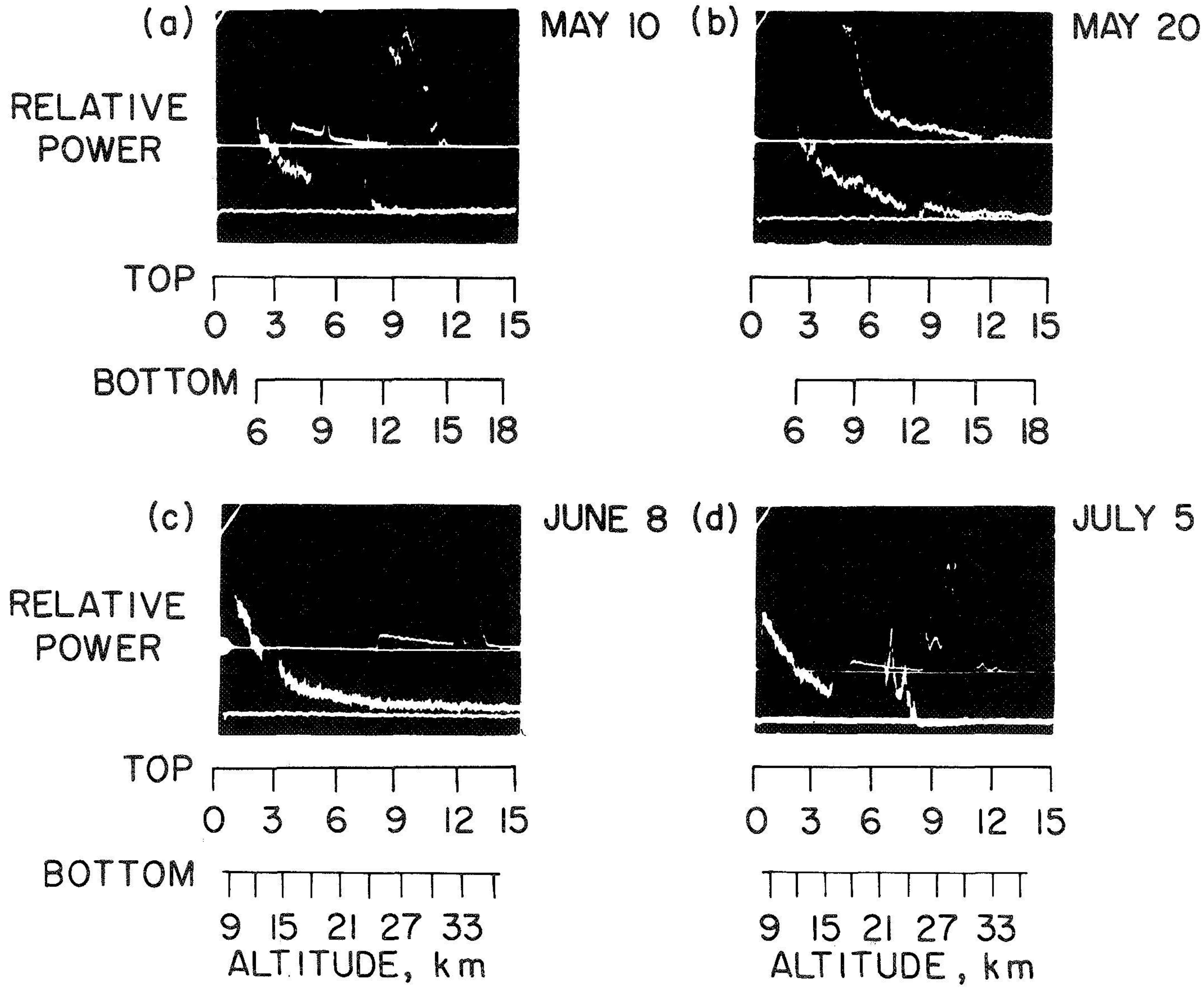

Figure 4.- Laser radar returns from clouds.

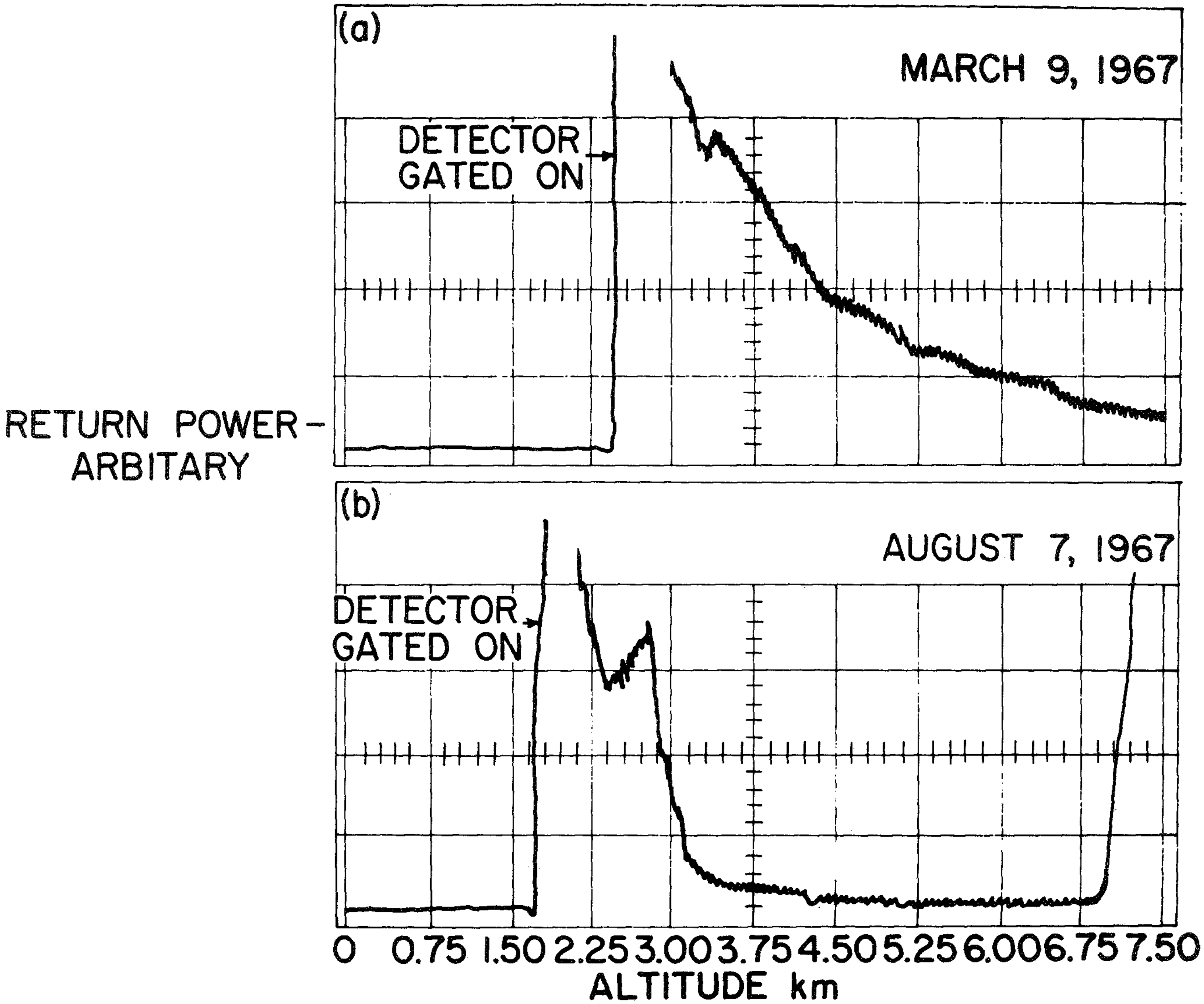

Figure 5.- Laser radar returns from turbulent regions.

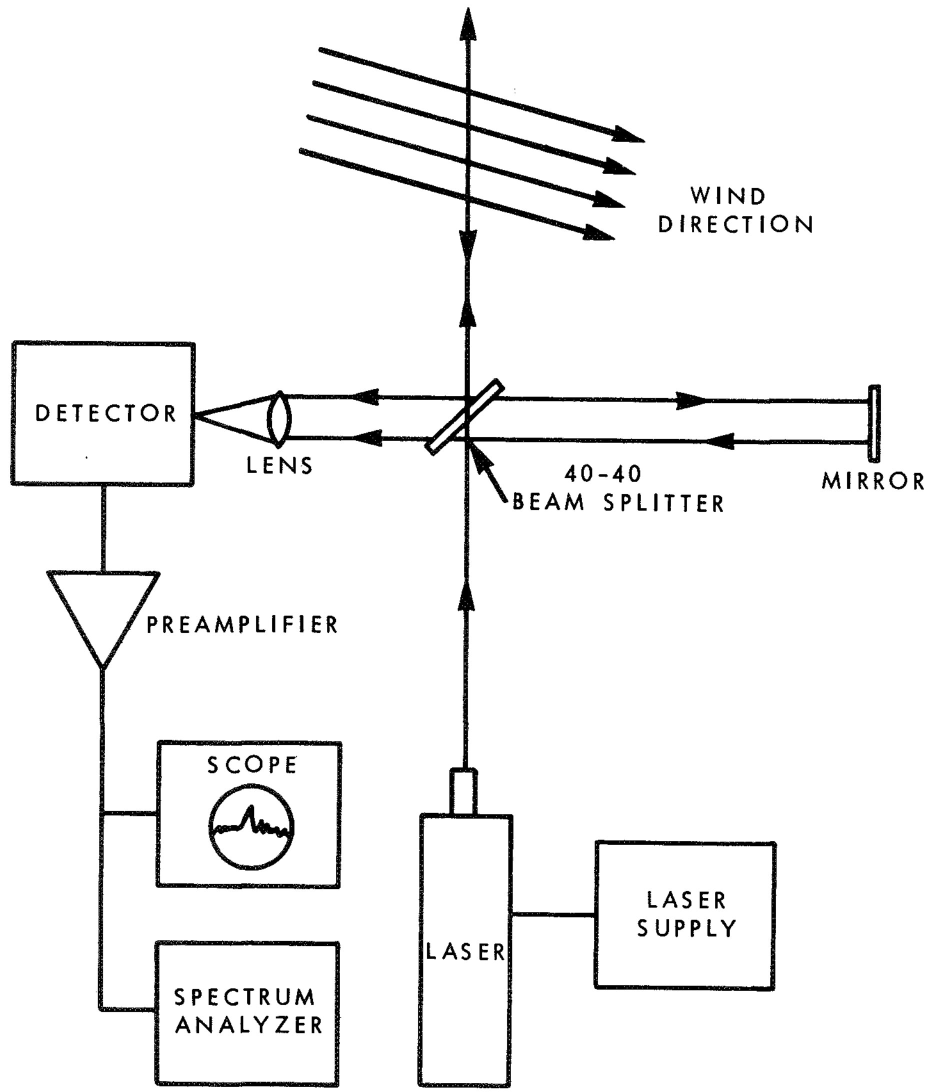

Figure 6.- Laser Doppler technique for wind velocity and turbulence measurements.

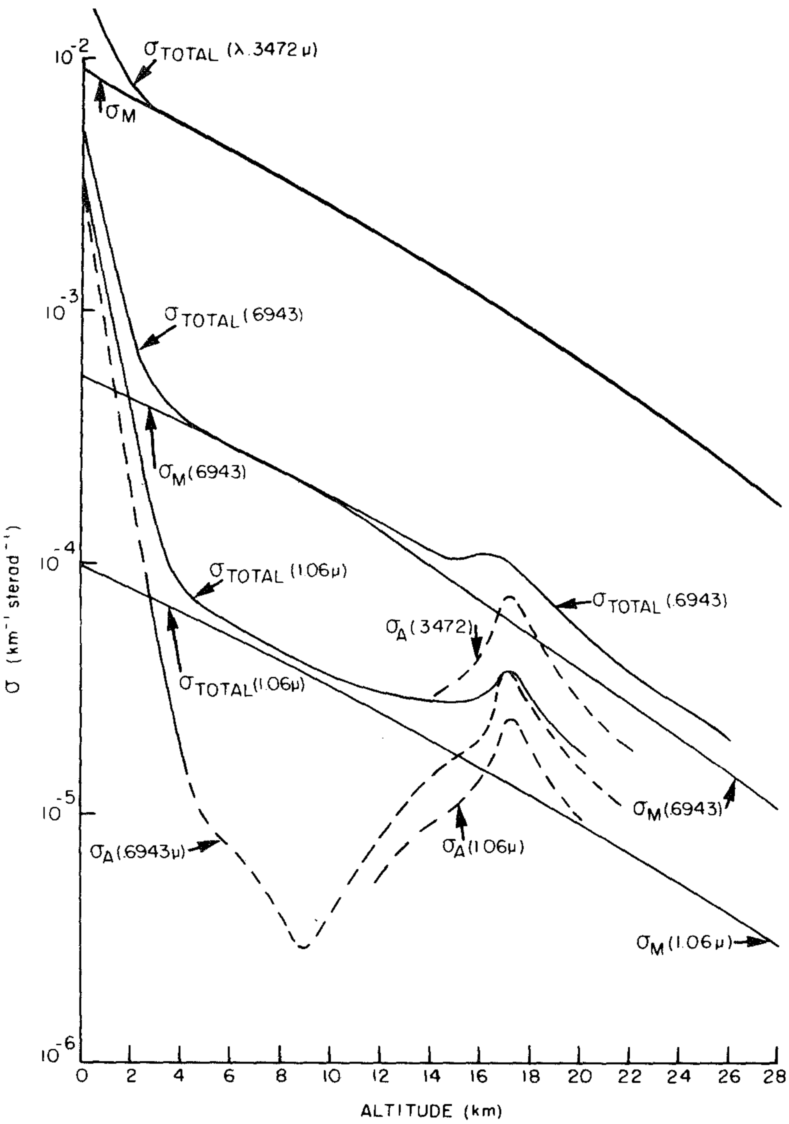

Figure 7.- Scattering cross section vs altitude at three laser wavelengths.

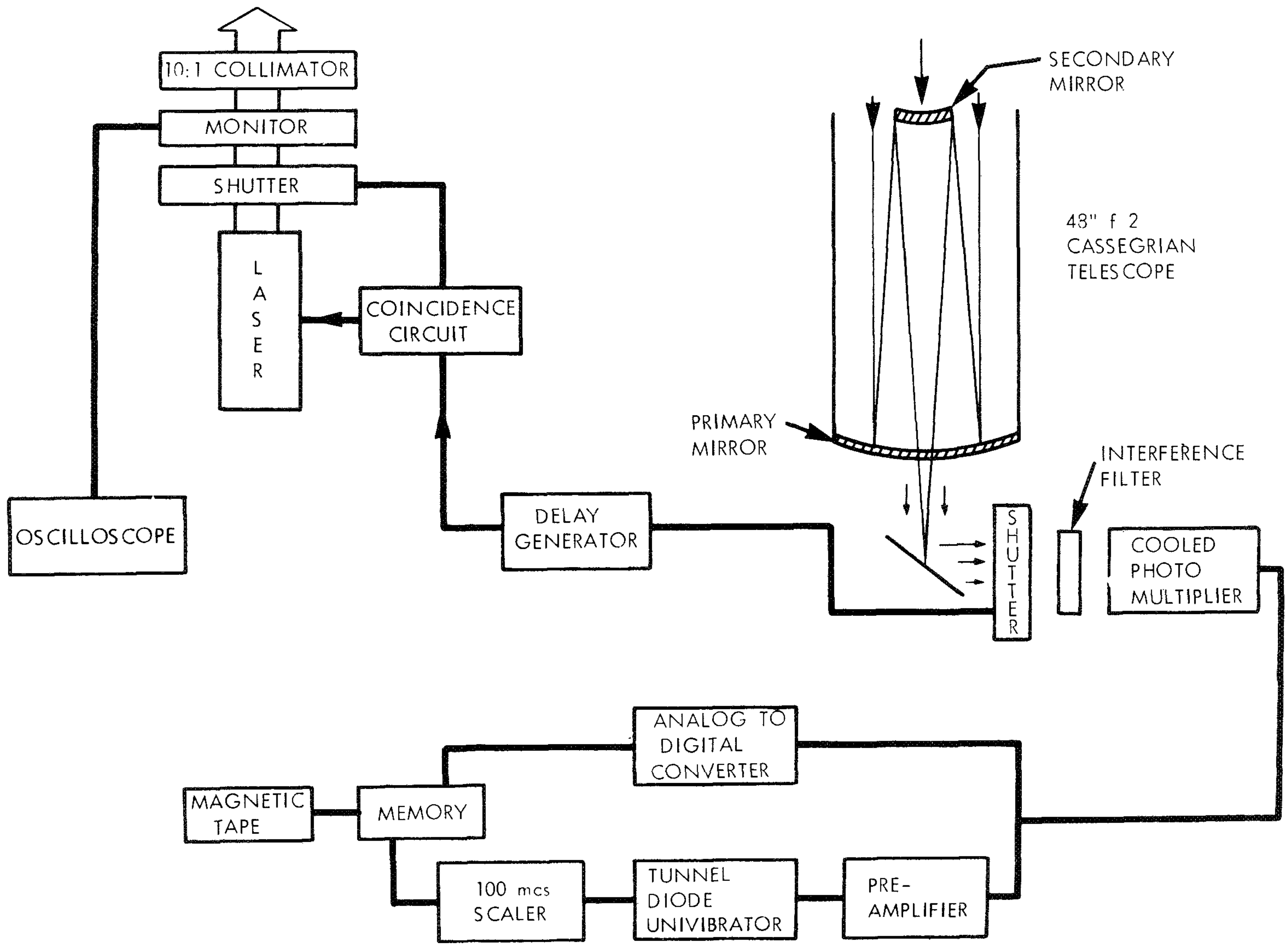

Figure 8.- Schematic diagram of laser radar system under development.

NASA-Langley, 1968